A critical review of laboratory and in-situ hydraulic conductivity measurements for the Boom Clay in Belgium

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ABSTRACT

The Boom Clay has been investigated for more than 30 years as a candidate host formation for the disposal of high-level and long-lived radioactive waste in Belgium. The very low hydraulic conductivity (on the order of 10^{-12} m/s) in combination with limited hydraulic gradients over the host formation (0.02 ~ 0.04) results in water flow in the Boom Formation being negligible and diffusion the dominant transport mechanism. The assessment of the long-term barrier function of the host clay formation in the framework of radioactive waste disposal requires rigorous quantitative characterization of key formation properties such as the hydraulic conductivity (K).

Hydraulic conductivities of Boom Clay measured through various testing techniques in the laboratory, *i.e.* tracer percolation experiments, constant head permeameter experiments and isostatic experiments, exhibit similar K values in the order of 10^{-12} m/s. Based on a large set of test samples, the impact of sample scale, hydraulic gradient range adopted in the tests, stress controlled methods and pre-existing fissures in the sample on the K value is shown to be quite limited. *In situ* measurements obtained from both several-centimetre long piezometer filters and percolation into a 7-metre long gallery and 21-meter long shaft at the HADES underground research facility yield K values that are very similar to values measured in the laboratory on samples of a few centimetres. This indicates that the K measurements for the Boom Clay obtained through various techniques are very consistent. K values measured on a centimetre-scale are also representative at the metre-scale, which is often the size of grid cells used in numerical simulations for long-term safety assessments.

Spatial analysis of K values across the Boom Clay at the Mol site reveals a typical profile with a very homogenous 61-m thick central part, i.e. the so-called Putte and Terhagen Members, which is also the least permeable part of the Boom Clay. The geometric mean of the vertical (K_v) and horizontal (K_h) hydraulic conductivities for the Putte and Terhagen Members at the Mol site are 1.7×10^{-12} and 4.4×10^{-12} m/s, respectively, with a vertical anisotropy K_h/K_v of about 2.5. Higher K values, but still low (10^{-12} to 10^{-10} m/s), are observed in the more silty zones above and below the Putte and Terhagen Members, i.e. the Belsele-Waas Member and the Boeretang Member, as well as in the double band of the lower Putte Member.

A regional analysis of vertical K variability of the Boom Clay in the northeast of Belgium based on test results from five boreholes shows an increase in hydraulic conductivity from the east towards the west. Statistical analyses indicate that the effect of the samples' stratigraphic position on hydraulic conductivity is strongly related to different grain-size characteristics. However, a general K – grain-size model does not explain the geographical differences in K values satisfactorily. Geographical differences can be best explained by different K – grain-size relationships at the different boreholes. The regional variation in K could be attributed in part to porosity, which in turn is related to the burial depth of the clay.

Keywords: geological disposal of radioactive waste; low permeable clay; hydraulic conductivity, laboratory/*in situ* measurements, grain-size.

1. Introduction

1.1 Background and objectives

Disposal in deep clay formations is one of the promising solutions for management of high-level and long-lived radioactive waste (NEA, 2008). In Belgium, the Boom Clay is studied as the reference host formation owing to its very low permeability in combination with other properties contributing to long-term confinement, such as strong adsorption capacity for many radionuclides, absence of preferential migration pathways, as well as its favourable creep and swelling properties. Furthermore, the low vertical gradient is an additional favourable characteristic for the Boom Clay in the north-eastern part of Belgium. (ONDRAF/NIRAS, 2001).

Low permeability is an essential property of any suitable host formation considered for nuclear waste disposal. Mazurek et al. (2009, 2011) studied the transport processes in the Boom Clay by investigating profiles of natural tracers dissolved in pore water. The linear profile of helium (He) across the Boom Clay has been shown by modelling to be entirely the result of steady-state Fickian diffusion transport across the clay. This implies that the very low hydraulic conductivity (K) (on the order of 10^{-12} m/s) together with a low hydraulic gradient (0.02-0.04) over the host formation results in a negligible water flow through the clay formation, hence molecular diffusion is the dominant transport mechanism. Radiological safety assessments have demonstrated the long-term safety of geological disposal in Boom Clay in part through illustrating the robustness of the disposal system by simulating the diffusive migration of radionuclides through the host clay formation (Mallants et al., 2001; Marivoet et al., 2002). In undisturbed Boom Clay water fluxes are negligible and determination of the hydraulic conductivity parameter is therefore principally for confirming that conditions of negligible flow are fulfilled. However, construction of a repository and the subsequent waste deposal would induce hydraulic-mechanical-thermal disturbances to Boom Clay close to disposal galleries. As a result, local variations of water pressure and the generation of important hydraulic gradients are inevitable, which further makes hydraulic conductivity an indispensable parameter for technical feasibility studies and radiological impact assessments that incorporate the excavation damaged zone surrounding disposal galleries (Chen et al., 2011).

Several studies previously conducted on Boom Clay consistently show hydraulic conductivity values roughly on the order of 10^{-12} m/s (Volckaert et al., 1995; Delage et al., 2000; Bernier et al., 2004; Wemaere et al., 2008; Le, 2008; Deng et al., 2011; etc.). These results were obtained independently using various hydraulic conductivity techniques on undisturbed clay cores of different scales and from different locations within the same geological unit. However, an integrated analysis addressing the potential effect of measurement scale on K values and the transferability of small scale K values to the larger regional extent is still lacking. A better understanding of these scale issues is indispensable for a rigorous and robust quantitative characterization of the hydraulic conductivity of Boom Clay. Such a characterization is not only needed as input to radiological impact assessment calculations, but is also pertinent to develop whole-of-system understanding and gain confidence in the intrinsic properties of the Boom Clay that contribute to long-term isolation of waste and delay and attenuate radionuclide releases.

At the Belgian nuclear research centre (SCK·CEN), determinations of hydraulic conductivities of the Boom Clay have been carried out since more than 30 years in various national (ONDRAF/NIRAS, 1989 and 2001; Yu et al., 2011) and international research programmes (Beaufays et al., 1994; Volckaert et al., 1995; Bernier et al., 2006). A large number of K measurements have been collected through fluid flow and tracer experiments both *in situ* at the HADES underground research facility (URF) in Mol, Belgium, and in the above-surface laboratories on samples from undisturbed clay cores. Such cores have been obtained from several deep boreholes in northeast Belgium in an area of several thousand km^2. Collation of this unique data set through this study has made it possible to address fundamental questions of scale dependency and transferability (i.e. from local to regional scale) of hydraulic conductivity.

The objective of this paper is therefore to present a synthesis of the hydraulic conductivities determined for the undisturbed Boom Clay in the past few decades. In this paper we address the following research issues: i) representativeness of small-scale laboratory K measurements for large-scale assessments, ii) evaluation of vertical variability and anisotropy of K values across the Boom Clay for individual boreholes, and iii) opportunities and limitations for transferability of K behaviour from the Mol site to the regional scale. To this end, this study makes use of K values obtained not only in the local investigation area at the Mol site, but also from four other boreholes named Zoersel, Doel-2b, Weelde-1 and Essen-1. In this way, the hydraulic conductivity can be investigated in the regional extent of the Boom Clay.

This paper will further serve as an important supporting reference in the framework of developing the first safety and feasibility case (SFC-1), which aims to collect the arguments and evidences to underpin the requirement that geological disposal of high level waste (HLW) in an argillaceous formation as the Boom Clay shall be safe and feasible.

1.2 Geological context of the Boom Clay

The Boom Clay, also called Boom Formation as stratotype of the Lower Oligocene, is a marine sediment of Tertiary, Rupelian age (30 Ma) occurring in northeast Belgium. It outcrops in a small west-east band from the Scheldt estuary area in the west (south of Antwerpen), along the Rupel river and the Demer river to the Meuse river in the east (south of Hasselt). The Boom Formation dips into the northeast direction with a slope of about 1-2 % with an increasing thickness (see Figure 1). At the Mol nuclear site, the Boom Formation lies between 190-290 m below the ground surface (Wemaere et al. 2008) (see Figure 1).

The Boom Clay belongs to Shepard's lithological classes of clayey silts and silty clays (Shepard, 1954). The reference mineralogical composition of the Boom Clay is given in Table 1, which is based on the analysis of 20 samples. Among them, 13 originate from the Mol-1 borehole and the other seven are from outcrop areas (Zeelmaekers et al., 2010 and 2011). The mineralogical composition of the Boom Clay is very homogeneous from a qualitative point of view. This has been proven at all levels of analysis (bulk rock composition, bulk rock chemistry, clay fraction composition and clay fraction chemistry, Zeelmaeckers, 2011). However, quantitatively, the proportions of the various minerals vary from one layer to another, as these are related to the grain-size variations: clay-rich layers comprise relatively more clay-minerals whereas silt-rich layers comprise relatively more quartz. Microbial degradation of organic matter during early-diagenesis resulted in the formation of framboidal pyrite and carbonates, typically developing septarian carbonate concretions. No evidence of other important mineral transformations is found in the Boom Clay.

The Boom Clay is also characterised by a banded structure essentially created by the alternation of silty and clayey beds ranging in thickness between 10 cm and 2 m. This banded structure is mainly the result of variations in grain-size, although variations in organic matter and carbonate content exist as well. They are enhanced by the presence of more bituminous organic matter in the dark clay beds and by horizons containing septarian carbonate concretions (Vandenberghe, 1978; Vandenberghe and Van Echelpoel, 1987).

At the scale of the regional hydrogeological system, the Boom Formation can be considered as one hydrostratigraphic unit, characterised by a very low permeability and low diffusion coefficient compared to the overlying and underlying sandy layers. The Boom Formation can be subdivided into four main stratigraphic units (Belgian Subcommission of Tertiary Stratigraphy, 2011). They are at the Mol site, from the basis to the top, the Belsele-Waas Member (~15.9 m thick at the Mol site), which is the siltiest part of the Boom Formation; the Terhagen Member (~15.6 m thick at the Mol site), characterised by pale grey clay and comprising the lowest proportion of coarser particles (sand or silt) and two dark bituminous zones; the Putte Member (~46 m thick at the Mol site), characterised by dark clay and the systematic presence of organic matter; and finally the Boeretang Member (this member is formerly referred as “Transition zone” and ~25.1 m thick at the Mol site), which is rich in silt. The Putte Member comprises one of the key horizons called the ‘‘double band” (db), situated in its lower part and which consists of two relatively coarse layers separated by a thin clay layer (Vandenberghe and Van Echelpoel, 1987).

1.3 Investigation areas

A large investigation programme has been running since more than 30 years to characterise the Boom Clay in Belgium. Although most of the Boom Clay characterisation has been carried out at the Mol investigation site (local investigation area), many efforts have been done since 1996 to characterise this formation over a much larger area (regional investigation area).

Of pivotal importance to the local investigation area is the HADES underground research facility (URF), which has been constructed in the middle level of the Boom Clay at 223 m depth in Mol since 1980. Numerous boreholes have been drilled from the HADES URF and provide substantial material for characterisation of the Boom Clay, including clay samples and borehole piezometers. A large number of samples have been used for hydraulic conductivity measurements through laboratory experiments. In addition, part of the data originates from *in situ* tests which provide information on the hydraulic conductivity of the argillaceous massif under current, assumed undisturbed conditions (Yu et al., 2011).

The regional investigation area is closely related to the regional extent of the Boom Clay deposits, which cover almost the entire northeast Belgium (Figure 1). In the mid-seventies, the Boom Clay has been first characterized in its outcrop area as well as through the first cored borehole drilled at the Mol site; it was further crossed (without sampling) through boring when the first groundwater level observation wells were installed that belong to the piezometric network in NE-Belgium (Labat, 2011). In the nineties, large data acquisition campaigns were set-up in order to provide (hydro)geological information (Wemaere et al., 2002, 2004a, 2004b and 2005), followed by a second campaign in 2005-2006 (Labat et al., 2008a and 2008b). Several exploration boreholes were drilled in the regional investigation area, including the municipalities of Mol, Zoersel, Rijkevorsel, Doel, Weelde, Turnhout, Dessel, Essen and Herenthout. These boreholes cut through the whole Boom Clay down to the underlying aquifer. Among them, the Mol, Zoersel, Doel, Weelde and Essen boreholes were fully cored.

2. Techniques for hydraulic conductivity measurements

Throughout the years, the hydraulic conductivity (*K*) of Boom Clay has been determined in several ways and at several scales, from core scale (several centimetres) to piezometer scale (several decimetres), up to gallery scale (several meters or tens of meters). The testing principles and interpretation theories are based on Darcy's law, which denotes a linear correlation between flow discharge and hydraulic gradient under steady-state conditions. Darcy's law is recognized to be applicable only within certain limits. Evidence for non-Darcy flow through clays has been widely reported and explanations for possible deviations are widespread (Horseman et al., 1996). In Opalinus Clay, conditions for Darcian flow to be applicable were demonstrated to exist for hydraulic gradients higher than 50, while non-linear flow was suggested to occur at hydraulic gradients < 1 (Croisé et al., 2004). In the following, a brief description of various testing techniques adopted by SCK•CEN to determine hydraulic conductivity is presented.

2.1 Laboratory experiments

The majority of hydraulic conductivity determinations on Boom Clay samples in the laboratory are based on two types of experiments. The first type is a percolation experiment used in the framework of radionuclide migration studies, aiming at determining physical transport parameters. While the primary objective of these tests is to determine the diffusion accessible porosity and apparent diffusion coefficient, the derivation of the hydraulic conductivity is a straightforward by-product. The second type of experiment is a hydraulic conductivity test using permeameter/isostatic/triaxial cells which are designed specifically to determine the hydraulic conductivity of low-permeable media.

Of primary concern to obtain reliable *K* data is to have an experimental procedure that permits appropriate sample collection and treatment prior to start the measurements. Clay samples have to be kept to a truly undisturbed condition by avoiding oxidation or any kind of contamination or geochemical reaction. The clay sample should be re-saturated before testing and the sample swelling should be avoided. To be representative of the *in situ* Boom Clay conditions, samples should be given sufficient time allowing for reconsolidations to *in situ* conditions.

For the *K* data reported here, great efforts have been undertaken to keep the clay plugs undisturbed and restored as much as possible to the *in situ* states. The sampling technique was optimised to reduce as much as possible disturbances of the samples during the drilling by adopting a cutting-edge wireline technique. The clay cores were kept in a 100-mm inner diameter and 1-m long PVC tube for each metre drilled. Afterwards, the cores were carefully conditioned to ensure a good preservation over a long time period. Transversal slices were sawed (without opening the PVC tube) and sealed at both ends with a PVC cap, and immediately wrapped in an aluminium-polyethylene film under vacuum conditions. The clay samples for *K* measurements were pressed in parallel or transverse direction into the cylindrical core sections for the determination of respectively vertical and horizontal hydraulic conductivities (K_v and K_h) (Wemaere et al., 2002; Aertsens et al., 2004; Wemaere et al., 2008). Before starting the K measurement, typically several weeks were used to allow full saturation of the clay samples.

Percolation experiment

For the percolation experiment the clay sample is confined between two filters in a permeation cell and continuously percolated with Boom Clay interstitial water under a constant pressure gradient over the clay plug. Tritiated water (HTO) and iodide were used as unretarded tracers. The water flowing out of the system is collected and the tracer concentration in the water is measured as a function of time. The tracer injection may occur at the inlet (boundary value problem - BVP) or is placed in the middle of a clay sample (initial value problem - IVP). The applied hydraulic pressure difference was mostly 1.23 to 1.35 MPa. The hydraulic conductivity K is obtained from the average measured water flux and the imposed hydraulic gradient. Detailed description of the percolation experiments can be found in Aertsens et al. (2004, 2008). The scale of the percolation test is relatively small. The diameter of the clay plug is 3.8 cm. The length of the sample is 3.2 cm for the BVP problem (sample volume ≈ 36 cm^3) or 7.2 cm with tracer injected in the middle for the IVP problem (sample volume ≈ 82 cm^3).

Permeameter test

Undisturbed 5-cm long and 3.8-cm diameter clay samples (sample volume ≈ 57 cm^3) were cut and fitted into a rigid stainless cylindrical cell with two sintered stainless steel filters at both ends. De-ionised water is injected at the bottom of the sample under a constant upward pressure of about 0.63 MPa. The outflowing water at the upper filter is collected in a hermetic flask, which is placed on a precision balance and allows regularly checking of the stability of the experiment. Tests are considered complete when measurements within five days indicate a stable flow through the clay sample (Wemaere et al., 2008).

Note that in both types of experiments, the cell is rigid and the top cap was manually controlled to touch the sample. Consequently, K values might be slightly overestimated given that the samples were not brought to their *in situ* lithostatic pressure by means of a reconsolidation process as would be typical of an isostatic or triaxial cell.

Hydraulic conductivity test using isostatic/triaxial cell

Isostatic/triaxial apparatus allows re-saturating and reconsolidating the clay sample to its *in situ* stress state prior to hydraulic conductivity testing by applying a stepwise compression. At SCK•CEN a custom-built isostatic cell controls the isostatic confining pressure and the effective stress with high precision for 30-cm long and 8-cm diameter cylindrical clay cores (Volckaert et al., 1995). The ~1500 cm^3 sample is left to consolidate and re-saturate under a confining stress of 4.4 MPa and a pore water pressure of 2.2 MPa, which is equivalent to the *in situ* interstitial pressure at the level of the HADES URF. When the equilibrium state is reached by evaluating the point at which the net inflow equals the outflow from the sample, the hydraulic conductivity testing sequence is initiated. The same principle with the triaxial cell was used by the British Geological Survey (BGS) on 4.9-cm diameter and 4.9-cm long Boom Clay samples for K_v and 2.45-cm long samples for K_h determination (Volckaert et al., 1995).

The large isostatic SCK•CEN-built cell is used to measure K on clay samples with a measurement volume about 26-times larger than that of the permeameter tests. This reduces considerably the influence of scale effects and inhomogeneities on the experimental results. The large size of the test specimen, however, requires strict control of the imposed hydraulic gradient. The pressure gradient along the large clay core was allowed to vary between 200-400, which is the maximum permissible value to keep a uniform stress field within the specimen, but large enough to allow a quick re-saturation of the samples (Ortiz et al., 1996). The drawback of low flows is that it prolongs the test duration to several months owing to the extremely low permeability of Boom Clay.

2.2 *In situ experiments*

In situ hydraulic tests on the Boom Clay were performed almost exclusively in the HADES URF, where the presence of the undisturbed clay allows for more complex borehole instrumentations. This paper only focuses on K determinations for undisturbed Boom Clay, therefore those filters located within the disturbed zone (i.e. excavation damaged zone) are excluded.

Single-point piezometer test

The principle of such tests is to use a stainless steel piezometer with a pervious screen buried in the porous clay matrix to measure the steady-state flow rate of the interstitial clay formation fluid from the piezometer at the hydraulic gradient created between the *in situ* pore water pressure and atmospheric pressure inside the piezometer. The fluid migration in an assumed isotropic and saturated medium can be described by Darcy's law (Beaufays et al., 1987). The measurement volume associated with the hydraulic conductivity estimated from the piezometer tests depends on the filter size and the *in situ* pore water pressure around the piezometer. Most of the piezometers have a screen diameter between 5 and 20 cm and a screen length between 2 and 9 cm. Therefore, the measurement or flow area of the single-point test is up to roughly several hundred cm^2; the corresponding measurement volume is easily several thousand cm^3 which is at least two orders of magnitude larger than that of the migration and permeameter tests discussed in the previous section.

Hydraulic conductivity determined from single-point piezometer tests is often some combination of vertical hydraulic conductivity (K_v) and horizontal hydraulic conductivity (K_h). One of the hypotheses for interpreting single-point tests is assuming isotropy of flow properties. In reality, the Boom Clay exhibits anisotropic hydraulic properties with $K_h \approx 2K_v$ (De Cannière et al. 1992; Wemaere et al., 2008), hence the values determined represent 'composite' or 'equivalent' values. When measuring on a vertical piezometer, K_h is the dominant component; for a horizontal piezometer, K_h and K_v are more or less equally contributing to the measured values (Bernier et al., 2004).

Interference test

An interference test measures hydraulic conductivity of clay with a multi-piezometer which consists of multiple tubular screens (generally 6 to 15 cm in diameter) in stainless steel mounted on the piezometer body directly placed in the clay formation from within the gallery. The piezometer filters are connected to the sampling point in the URF by small diameter stainless steel tubes. The filter can be placed in vertical or horizontal direction which yields values of respectively horizontal and vertical hydraulic conductivity. The water is collected into closed containers in order to prevent evaporation of the sampled water. The collected water is regularly weighted at a schedule of several days or weeks. *In situ* pressure is usually measured using pressure transducers mounted on the piezometer body. During the measurement, the valve on one piezometer filter is opened making a connection to the URF gallery which is at atmospheric pressure, and measurements of the pressure evolution in the surrounding filters are used for K determination (De Cannière et al., 1992; Volckaert et al., 1995).

Large scale *in situ* test

A single large-scale hydraulic experiment, often called macro-permeameter test, was performed in 1993 in a separate experimental shaft and gallery connected to the main gallery of the HADES URF. The small shaft and gallery have an external diameter of two metres, with a length of 21 m and 7 m, respectively. Thirty-centimetre thick concrete blocks were placed as a lining against the shaft and gallery wall. A 6-mm thick water permeable LINE-X board was placed between each block layer, thus the entire concrete lining would have thin permeable sections similar to a filter. The basic principle of the experiment was to have the experimental shaft and gallery act as a large borehole filter (macro-permeameter with a flow cross-sectional area of about 190 m^2) and a corresponding measurement volume of at least several hundred m^3. The entrance to the shaft was sealed off from the main URF gallery with a glass cover to prevent evaporation of water by the ventilation of the main URF gallery. Three humidity sensors were emplaced in the middle of the gallery, at the top and the bottom of the shaft to control the validity of the zero-evaporation losses assumption. Water level measurements in the so-called borehole filter were realized by two independent devices, i.e. the capacitive level gauge and a manual reading device. The water flow through the void spaces of the macro permeameter was observed for a total of 1050 consecutive days (Ortiz et al., 1996).

2.3 Discussion about different experimental techniques

Most of the K values for Boom Clay were obtained through percolation and permeameter tests, on a small size clay plug with a volume varying from a few 10 to 100 cm^3. For such testing techniques and for such scale range, it was found that values of hydraulic conductivity are not sensitive to the scale of the sample (Marivoet et al., 2009).

In laboratory tests, water evaporation is sufficiently prevented by using a closed steel tank system and a syringe at the inlet and outlet, respectively. In the in-situ tests with piezometers, the water is collected in a closed systems and evaporation is therefore negligible. In the large-scale drainage experiment, several precautions were taken to limit water evaporation: the main experimental gallery located above the drainage experiment is lined with cast iron, which is considered to be totally impervious; a glass plate covers the access to the exploratory shaft in which the drainage experiment takes place (Ortiz et al., 1996).

Imposed hydraulic gradients in percolation and permeameter tests (from ~1300 to ~4200) are much larger than the natural hydraulic gradient, *i.e.* 0.02~0.04 at Mol. Given the very low permeability of the Boom Clay it is practically impossible to perform laboratory K

measurements at such low natural gradients. The imposed hydraulic gradient under laboratory conditions must be high enough to generate a measurable water flow over a sensible time-scale. This could also avoid the 'threshold gradient effect' to ensure Darcian flow (Croisy et al., 2004). The increased hydraulic gradients during K measurements are achieved by raising the water pressure, which theoretically leads to variations of the local effective stress and thus may result in local variability in the hydraulic conductivity within a sample (Volckaert et al., 1995). However, the results imply that for constrained Boom Clay samples used in permeameter tests and within the studied range of gradients, the influence of the gradient on the sample-scale hydraulic conductivity is negligible and Darcy's law is still valid (Volckaert et al., 1995; Marivoet et al., 2009).

The K measurements on Boom Clay from Coll (2005) using triaxial experiments show that K decreases from 6.3×10^{-12} to 1.2×10^{-13} m/s when the confining pressure increases from 0.4 MPa to 32 MPa. A similar decreasing trend in K with confining pressure was observed by Horseman et al. (1987). For the *in situ* stress level of 2~2.3 MPa, the hydraulic conductivity varies between 1×10^{-12} m/s to 3×10^{-12} m/s. Vertical hydraulic conductivities obtained through isostatic cells by SCK·CEN range between $1.62\sim2.02\times10^{-12}$ m/s (Ortiz et al., 1997). The geometric mean values of hydraulic conductivity measured on triaxial cell by BGS are 1.3×10^{-12} m/s and 3.9×10^{-12} m/s for K_v and K_h, respectively (Ortiz et al., 1997). All these stress-controlled tests give a similar range in K values as those obtained from non stress-controlled testing techniques, *i.e.* permeameter tests and migration tests (see further).

In the recent EC TIMODAZ project (Delage et al., 2010), 40-mm diameter and 40-mm long cylindrical Boom Clay specimens collected perpendicular to the bedding were installed in the triaxial apparatus developed by Coll (2005) to measure hydraulic conductivities under various temperature and stress conditions. A K value of 3.8×10^{-12} m/s was obtained for a Boom Clay sample during the consolidation phase. However, X-ray tomography prior to testing reveals that pre-existing fissures are inevitable in the clay specimen (Delage et al., 2010). This implies that K values measured on the clay sample in the laboratory are likely overestimated, therefore are on the conservative side from the safety point of view. The degree of disturbance of samples to be tested in the laboratory is always an issue and underscores the need for comparison with values measured under the *in situ* state (see next section).

3. Hydraulic conductivity data at the Mol site

A large fraction of the hydraulic conductivity data of the Boom Clay at the Mol site is associated with the Mol-1 borehole, which was drilled at about 50 m from the second shaft of the HADES URF. The Mol-1 borehole was drilled in 1997, down to a depth of 567.65 m below the ground surface. It was cored from 145.37 to 326.98 m, completely covering the Boom Formation. Investigation at the Mol-1 borehole provides a detailed hydraulic conductivity profile of the entire Boom Clay, at a vertical spatial resolution of 1~2 m. According to the orientation of the clay core (parallel or transversal to the stratigraphic plane), respectively K_h and K_v were measured by means of permeameter and percolation tests (Wemaere et al., 2002 and 2008). The main stratigraphic sub-units for the Mol-1 borehole together with their respective K_h and K_v values are listed in Table 2.

Additionally, the HADES URF, where *in situ* tests were performed and numerous Boom Clay samples were taken for laboratory K determination, provides supplementary information on K values for the central part of the Boom Formation. More than 50 determinations of hydraulic conductivity have been performed *in situ*, by single point piezometer tests or by interference multi-piezometer tests. Furthermore, there is one large scale *in situ* test which concerns the experimental shaft and its associated experimental gallery – for dimensions see higher (Beaufays et al., 1987; De Cannière et al., 1992 and 1994; Volckaert et al., 1995; Ortiz et al., 1996 and 1997; Bernier et al., 2004; Yu et al., 2011).

Except piezometer R13U reaching the Boeretang Member and piezometer MORPHEUS reaching the Terhagen Member, all the other *in situ* tests were carried out in the Putte Member.

Figure 2 provides a vertical profile of the K values for the entire section of the Boom Formation at the Mol site with indication of the main stratigraphic sub-units and the test type. The clay, silt and sand content profile measured from the Mol-1 borehole are illustrated at the right side of the graph. Geometric mean vertical (K_v) and horizontal (K_h) hydraulic conductivities derived from laboratory tests and equivalent hydraulic conductivities (K) obtained from *in situ* tests are illustrated respectively by the dashed, dash-dotted and solid lines for each sub unit. For Putte and Terhagen Members, the equivalent K from *in situ* tests lies between K_v and K_h derived from the laboratory tests. The reason was given in the previous section addressing the working principle of the single point piezometer test.

At first glance the vertical variations in K for the whole Boom Clay section indicate that the highest K_v values are clearly situated in the Belsele-Waas Member, the Boeretang Member and the "double band" (db) (Figure 2). Except for the laboratory K measurements from the Mol-1 borehole providing K information for all four sub-units, all *in situ* test locations are within the Putte and Terhagen Members (except the piezometer test R13U which lies in the upper Boeretang Member). Therefore, the following investigation about differences in variability in K according to the sub units is only based on hydraulic conductivities measured by means of permeameter tests and percolation tests on samples from the Mol-1 borehole. Table 2 summarizes the K_h and K_v values for each sub-unit measured at the Mol-1 borehole. The overall highest mean K values and highest heterogeneity are measured for the Belsele-Waas Member (geometric mean $K_v = 1.6\times10^{-11}$, $K_h = 5.7\times10^{-11}$ m/s; the standard deviation s of the log transformed K values is 1.0 and 1.2 for respectively K_v and K_h), and are attributed to its high sand content of 22% on average. The Putte and Terhagen Members, which represent the central part of the Boom Formation, show the lowest overall mean values of hydraulic conductivity and display the lowest heterogeneity with depth (the standard deviation s of the log transformed K values is smaller than 0.2), except for the sandy "double band" (db) in the lower Putte Member. The very silty bed of the Boeretang Member (average silt content of 70%) yields similar or slightly higher K values than the Putte and Terhagen Members, but with some more variations according to depth.

The summary of hydraulic conductivities measured from various techniques for the Putte and Terhagen Members in Figure 3 reveals a very consistent estimate of the hydraulic conductivity considering the 95% confidence intervals. *In situ* measurements made on a few decimeters long filters and on the large-scale *in situ* test at the HADES URF yield K values on the same order of magnitude (geometric mean K=3.5×10^{-12} m/s for piezometer tests and 1.4×10^{-12} m/s for large-scale *in situ* test) that are very similar to values measured in the laboratory on centimeter scale samples (geometric mean K_v = 1.9×10^{-12} and K_h = 4.3×10^{-12} m/s). Consequently, parameter values measured on a centimetre scale can be applied to a scale of tens of metres, in so far as the considered clay volume can be considered to be homogeneous for that parameter (Marivoet et al., 2009).

Based on all the laboratory (29 K_h and 119 K_v) and interference tests (2 K_h and 2 K_v) carried out at the Mol site for which directional values could be unequivocally defined, the geometric means of the vertical and horizontal hydraulic conductivities for the Putte and Terhagen Members are respectively 1.7×10^{-12} and 4.4×10^{-12} m/s with an anisotropy ratio K_h/K_v of about 2.5.

4. Regional variability in the hydraulic conductivity of the Boom Clay

An intensive characterisation programme on small core plugs was undertaken at four additional locations, i.e. the Zoersel, Doel-2b, Weelde-1 and Essen-1 boreholes (Fig. 1). These boreholes were drilled in the regional investigation area which covers about 1100 km^2 of the occurrence area of the Boom Clay in northeast Belgium. Together with the Mol-1 borehole, these additional boreholes allow a systematic characterization of the spatial variability in hydraulic conductivity of the Boom Clay at the regional scale. Because the depth of the Boom Clay is different for different locations, effects of compaction (e.g. porosity) on K could be evaluated. Another source of K variability that is investigated includes grain-size distribution.

Figure 1 illustrates the regional extent of the Boom Clay, its thickness, its depth below surface, and the locations of the five investigation boreholes. Note that at the Doel-2b location the top of the Boom Clay is at a depth of 50 m while at Weelde-1 it is at roughly 250 m below surface, owing to the northeast oriented downward slope of 1-2%. At these two locations, the thickness of Boom Clay is respectively ~25 and ~125 m. In all five boreholes, contiguous coring was performed followed by core sample collection for hydraulic conductivity determination using the same permeameter and percolation experiments as discussed above.

Detailed descriptions and analyses of the borehole cores, interpretation of the geophysical logging performed in the open-hole and hydraulic conductivity measurements are available in Wemaere et al. (2002, 2004a, 2005, 2008) and Labat et al. (2008a). Table 3 summarizes the Boom Clay hydraulic conductivity data using identical stratigraphic sub-units at the regional scale as was previously used for the Mol-1 borehole (Table 2). The Terhagen Member and the Putte Member are merged and treated as one single unit due to their similarity in hydraulic and transport properties. Spatial variability in hydraulic conductivity according to the stratigraphic sub-units is displayed in Figure 4.

A typical K profile of the Boom Clay observed in all boreholes exhibits a less permeable and relatively more homogeneous central Putte and Terhagen Member, and a more permeable and heterogeneous overlying Boeretang Member and underlying Belsele-Waas Member. With respect to the vertical hydraulic conductivity, the Essen-1 borehole has a pronounced higher global mean value for the whole Boom Clay ($K_v = 8.5\times10^{-12}$ m/s) than the other boreholes. The Mol-1 borehole appears to be the least permeable ($K_v = 2.8\times10^{-12}$ m/s). A general increasing trend in overall Boom Clay vertical hydraulic conductivity is observed from east towards west, *i.e.* increasing from Mol (2.8×10^{-12} m/s) → Weelde (4.0×10^{-12} m/s) → Zoersel (5.5×10^{-12} m/s) → Doel (8.0×10^{-12} m/s) → Essen (8.5×10^{-12} m/s). A similar trend is observed for K_h with Essen-1 having the highest overall K_h (4.7×10^{-10} m/s).

Generally, the vertical hydraulic conductivities of the Putte and Terhagen Members are on the order of 10^{-12} m/s. The variation is also the smallest for the Putte + Terhagen unit with the standard deviation s of the log-transformed K values (considering both K_v and K_h) between 0.1 and 0.2, except for the Doel-2b and Essen-1 boreholes where s reaches 0.8. The Boeretang Member is slightly more permeable than the Putte + Terhagen Members in the Doel-2b, Essen-1 and Mol-1 boreholes (less than a factor 2), and somewhat more permeable in the Weelde-1 and Zoersel boreholes. The Belsele-Waas Member is only slightly more permeable than the Putte + Terhagen unit in Weelde-1 (a factor of 2.6 for K_v and 3.6 for K_h), but much more in other boreholes, especially reaching a factor of 160 for K_v and 370 for K_h in the Zoersel borehole. For all five boreholes the Belsele-Waas Member displays the highest standard deviation of the log-transformed K values (considering both K_v and K_h), i.e. from 0.4 to 1.2. From all boreholes tested, the Weelde-1 borehole exhibits the lowest variations of K (considering both K_v and K_h) in the Belsele-Waas Member, while Mol-1 displays the highest variation (s = 1.0 for K_v and s = 1.2 for K_h).

Most of the analyses yield an anisotropy ratio K_h/K_v at the sample scale (about 60 cm^3 in permeameter test) of about 2 (Wemaere et al., 2002, 2004a, 2004b, 2005; Aertsens et al., 2005; Labat et al., 2008a, 2008b). However, calculating the harmonic means at the scale of the formation thickness (~100 m), justified by the fact that the Boom Clay can be considered at the regional scale as a single aquitard unit, leads to an increased global anisotropy ratio at the formation scale of about 3-7 in the case of the Mol-1, Doel-2b and Weelde-1 boreholes and nearly 60 for the Zoersel and Essen-1 boreholes. It is the contrasting nature of the individual

Boom Clay members, in particular the Belsele-Waas Member, that is responsible for the increased calculated anisotropy at the formation scale (Wemaere et al., 2008).

5. Statistical interpretations of the regional variance of *K*

Given the large amount of available grain-size data at each borehole, grain-size variables could be used to potentially explain the variance of hydraulic conductivity at the regional scale. In previous studies by Huysmans (2006) and Jeannée (2009), the variable *d*40, which is defined as the grain-size for which 40% of the particles are finer than this diameter (µm), was shown to have the best correlation with hydraulic conductivity data. The grain-size statistical analyses at the five boreholes confirm the finer size of materials for Boom Clay: the mean values of *d*40 are 7.0 µm, 2.4 µm, 2.8 µm and 18.1 µm for Boeretang, Putte, Terhagen and Belsele-Waas Members respectively (Jeannée, 2009). Wemaere et al. (2008) built relationships between the logK_v and combinations of significant grain-size parameters using multiple regression.

In the present study F- and t-tests were applied sequentially to the K_v data to explore the differences between the mean hydraulic conductivities for boreholes (geographical component) and members (stratigraphic component). The group labels in Table 3 show that at a significance level $\alpha = 0.05$ the Mol borehole differs significantly from all other boreholes but not from the Weelde borehole when data from all members is combined. This is further true when the means are compared per stratigraphic member, i.e. for the Putte, Terhagen and Boeretang members. Also for these three members the Weelde borehole is the only borehole not significantly different from Mol, but it is also not different from the other locations.

To explore the reason for this difference between boreholes, two-way analysis of variance (ANOVA; Scheffé, 1999) was employed to attribute the variance of *K* to the different stratigraphical members and borehole locations. To assess the influence of grain-size parameter $d40$ on K_v, a set of models with increasing complexity was fitted to the data and included in the ANOVA. ANOVA was performed on the residuals of these models for partitioning the total K_v variance into the different components. The first model is a linear regression of K_v as function of $d40$ (fixed effect of $d40$). The next two models are linear mixed effect models, that include, besides the fixed effect of the first model, a random effect for each stratigraphical member, or for each borehole location. In other words, for each stratigraphical member or borehole a separate linear regression model was fitted between the residuals of the former model and $d40$. The results are shown in Table 4, relative to the original data that serves as reference.

In the ANOVA, the total variance of the K_v dataset is divided in parts that are explained by the following factors: association with the different boreholes, the stratigraphic position within the borehole, and their combined effect. For the original data, 46% of the hydraulic conductivity variability is explained by the stratigraphic position of the samples (i.e. one of the four stratigraphic members), while only 16% is explained by the borehole location (Table 4). Unexplained variance amounts to nearly 28%. In other words, irrespective of the geographical location of the borehole, hydraulic conductivity variability is mainly governed by its association to a given stratigraphic member (46%), while the combined effect of stratigraphy and geographical location of the borehole accounts for only 10% of the variability. If the fixed effect of grain-size ($d40$) is taken into account, the percentage of variance explained by the stratigraphic position drops to 3%. This indicates that the effect of the sample's stratigraphic position on hydraulic conductivity is strongly related to different grain size characteristics. However, the part of the total variance explained by the boreholes' location remains relatively large at 13%, indicating that a general K_v – grain size model does not explain the geographical differences (i.e. borehole locations) in K_v values satisfactorily. Overall, including the fixed effect of $d40$ reduced the total variance to 37% of the original data.

The second model accounts for the additional random effect of stratigraphy (taking away all variance explained by this factor), but still shows a significant part of the variance explained by the borehole locations (7%). Thus developing a *d*40-based mixed effects model per stratigraphic member reduces the variance for the factor stratigraphy to zero, but significant differences between the boreholes remain. The total remaining variance decreases from 37% for the linear regression (fixed effect) to 24%. The third model accounts for the random variation due to borehole locations (taking away all variance explained by the borehole factor); no significant differences remain, and most of the variance left is unexplained. The remaining total variance amounts to 18% of the original data variance. Thus, the most efficient way to explain the variance in the data is to develop mixed effects models for the borehole factor, rather than by stratigraphic member. Both linear mixed models (with fixed and random effect) are compared with the linear regression (fixed effect) in their performance using the classical log-likelihood ratio test, with the significance of the test statistic respectively equal to 0.03 and 0.0001. Hence, the linear regression model is rejected in favour of the linear mixed effects models. In other words, the latter models give a significantly better description of the data than the former. Figure 5 shows the boxplots for both the K_v data and *d*40. While K_v shows different ranges for the different boreholes, *d*40 is quite similar. This explains the previous conclusion that different grain-size – K_v relationships are needed for explaining variability between the different boreholes. Figure 6 illustrates the different K_v - grain-size relationships obtained for the last mixed effects model (random effect by borehole). Different regression lines indicate that different grain-size relationships are needed to couple K to grain-size at each borehole. The regression lines for the Weelde-1 and Mol-1 boreholes show the lowest absolute K_v-values, as well as the smallest slopes.

Indeed, a trend in K_v with depth can be found in the Boom Clay, if the heterogeneous layers are filtered out and if only the low K_v values (below 10^{-11} m/s) of the Putte member are considered (Figure 7). The previously discussed ANOVA results are now revisited by applying a correction according to this depth-trend. This is done by subtracting the trend from the original data pertaining to the Putte member and adding back the geometric mean of the data on which it was fitted. The ANOVA then shows that the variance explained by the borehole location decreases, but remains significant, even with the random effect of stratigraphy (Table 5). This means that the effect of depth is only partly responsible for the regional variation. At least 5% of the total K_v variance is caused by the different geographical locations, which cannot be explained by the sample depth.

To locate the significant differences, a second iteration of F- and t-tests was performed on the residuals of the mixed effects model with a random component for each stratigraphical member, for the trend-corrected data. The results are similar to those obtained for the non trend - corrected data (Table 4), probably because only for the Putte member such trend correction was applied. Nevertheless, the mixed effects models, either with or without trend correction, are superior in explaining K_v variation than the fixed effect model.

In a recent study for Boom Clay based on a single borehole (Deng et al., 2011), a linear relationship between the logarithm of K and porosity expressed as void ratio (volume of void space to volume of solids) was observed. We evaluated if the trend in K with depth shown in Figure 7 could also be explained by porosity variations. For this purpose we used porosity data from the five boreholes measured on each sample that was also subjected to a permeameter test. However, no trend was found between porosity and depth, even excluding the variance caused by grain size. No clear relationship could be found between the logarithm of K and void ratio. Furthermore, inclusion of the porosity data in the ANOVA analysis did not lead to superior models for explaining the variance (results not shown). There could be several explanations for the lack of such relationship. First of all, reconsolidation was not applied during the permeameter tests, which might have led to substantial overestimation on these porosity data, with the degree of overestimation becoming larger as the sample depth increases. Also, some of the variability in the porosity data may have confounded the presumed relationship with *K*. Therefore, a mean porosity was calculated for each of the five boreholes using only data within the interquartile range (between 25th and 75th percentile; from now on referred to as 50% trimmed mean). The 50% trimmed mean porosity over the Boom Formation was 42.5%, 42.3%, 40.9%, 40.3% and 35.7% for the Doel-2b, Essen-1, Zoersel, Weelde-1 and Mol-1 boreholes, respectively. This decrease in porosity is consistent with the decrease in the 50% trimmed mean K_v as presented in Figure 8. In other words, using a more robust estimator of the mean (i.e. the 50% trimmed mean) yields a simple model to explain the mean *K* variation at the regional scale. Effects of other factors on *K* variability such as mineralogy, carbonate content, etc., could not be investigated in this study due to lack of information.

Further corroboration of depth-related trends and other trends is proposed as these offer practical tools to develop understanding of *K* variation at the regional scale. This may ultimately lead to transferring the very thorough understanding of *K* behaviour at the Mol site to other locations with potentially different grain-size distributions and/or Boom Clay stratigraphic members at different depths.

6. Conclusions

The hydraulic conductivity of the Boom Clay has been the subject of intensive research for about thirty years. These studies are part of the long-term research programme investigating the feasibility and safety of radioactive waste disposal in this geological formation in Belgium. The Boom Clay is roughly 100-m thick at the Mol-1 borehole. It is subdivided into four main stratigraphic units. These are, from the basis to the top, the Belsele-Waas Member, the Terhagen Member, the Putte Member and the Boeretang Member.

K values at the Mol site are derived from hydraulic laboratory tests conducted on small (cm scale) clay samples collected from the HADES URF and from the Mol-1 borehole or from larger-scale (dm to m scale) *in situ* piezometer tests in the HADES URF mainly for the Putte and Terhagen Members. The highest mean and (most variable) *K* values for the lowermost Belsele-Waas Member (geometric mean K_v =1.6×10^{-11}, K_h = 5.7×10^{-11} m/s, the standard deviation *s* of the log-transformed K_{v} values is 1.0 and 1.2, respectively) are attributed to its high sand content (~22%). The Terhagen Member and the Putte Member can be treated as one single ~60-m thick hydraulic unit at the Mol site due to their similarity in hydraulic and transport properties. They form the most homogeneous (standard deviation of the log-transformed K_v and K_h at Mol-1 borehole is 0.2 and 0.1, respectively) and the least permeable part of the Boom Formation, except for 1-2 thin layers with relatively higher permeability known as "double band" in the lower part of the Putte Member. Nearly all the *K* values measured for the Putte and Terhagen Members at the Mol site are in the approximate range 1.5 – 8×10^{-12} m/s. Based on all *K* measurements at the Mol site for which directional values can be unequivocally defined (including 29 K_{h} and 119 K_{v} laboratory tests and 2 K_{h} and 2 K_{v} interference tests), the geometric means of the vertical and horizontal hydraulic conductivities for the Putte and Terhagen Members are respectively 1.7×10^{-12} and 4.4×10^{-12} m/s with an anisotropy ratio $K_{\mathrm{h}}/K_{\mathrm{v}}$ of about 2.5. The very silty Boeretang Member (average silt content of 70%) yields similar or slightly higher *K* values than Putte and Terhagen Members, but with some more variations according to depth.

The regional variability in hydraulic conductivity of the Boom Formation was examined at four additional boreholes (Doel-2b, Essen-1, Weelde-1 and Zoersel) covering an area of about 1100 km^2. Using the same laboratory measurement techniques as for the Mol-1 borehole, i.e. permeameter and percolation tests, the overall geometric mean of the hydraulic conductivity for the Putte and Terhagen Members from the five boreholes was estimated to be

4.3×10^{-12} m/s for the vertical hydraulic conductivity and 8.7×10^{-12} m/s for the horizontal hydraulic conductivity, both with a standard deviation of 0.2.

A typical vertical *K* profile of the Boom Clay observed in all five boreholes includes the least permeable and relatively homogeneous Putte and Terhagen Members, and the more permeable overlying Boeretang Member and underlying Belsele-Waas Member. With respect to the vertical hydraulic conductivities, the Essen-1 borehole has a pronounced higher global mean value for the whole Boom Clay (8.5×10^{-12} m/s) than the other boreholes, and the Mol-1 borehole appears to be the least permeable one (2.8×10^{-12} m/s). An increase in overall Boom Clay vertical hydraulic conductivity is observed from east towards the west, *i.e*. increasing from Mol (2.8×10^{-12} m/s) $\rightarrow$ Weelde (4.0×10^{-12} m/s) $\rightarrow$ Zoersel (5.5×10^{-12} m/s) $\rightarrow$ Doel (8.0×10^{-12} m/s) $\rightarrow$ Essen (8.5×10^{-12} m/s). A similar trend is observed for K_h with Essen-1 having the highest overall K_h (4.7×10^{-10} m/s).

The statistical analysis of the five boreholes implies that regional variation in K_v of the Boom Clay can be attributed in part to the porosity variation of the Boom Clay, which is related to the burial depth of the clay and which is increasing from the southwest towards the northeast. A second variable which explains most of the variation in K_v is the grain-size parameter *d*40: the most efficient way to explain the variance in the data is to develop *d*40 regression models for each borehole separately rather than by stratigraphic member. There are further indications that decreasing porosity with depth explains part of the *K* variation across the investigated area. The results finally demonstrate that the hydraulic conductivity of the Boom Clay, especially in the Putte and Terhagen Members, remain very consistent even for the relatively large geographical area of northeast Belgium investigated here, but unexplained regional variations still exist until today.

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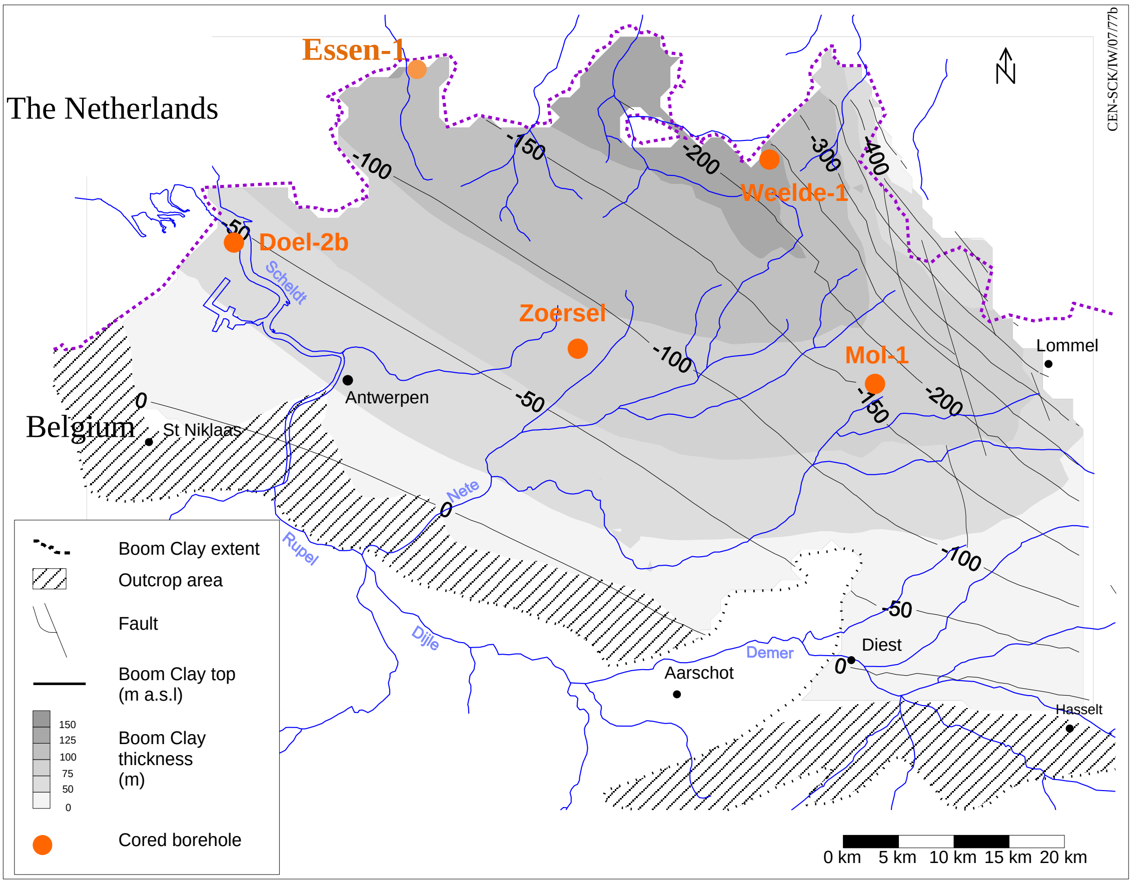

Figure 1: Geographic extent of the Boom Clay in NW Belgium with indication of depth and thickness (after Wemaere et al., 2008).

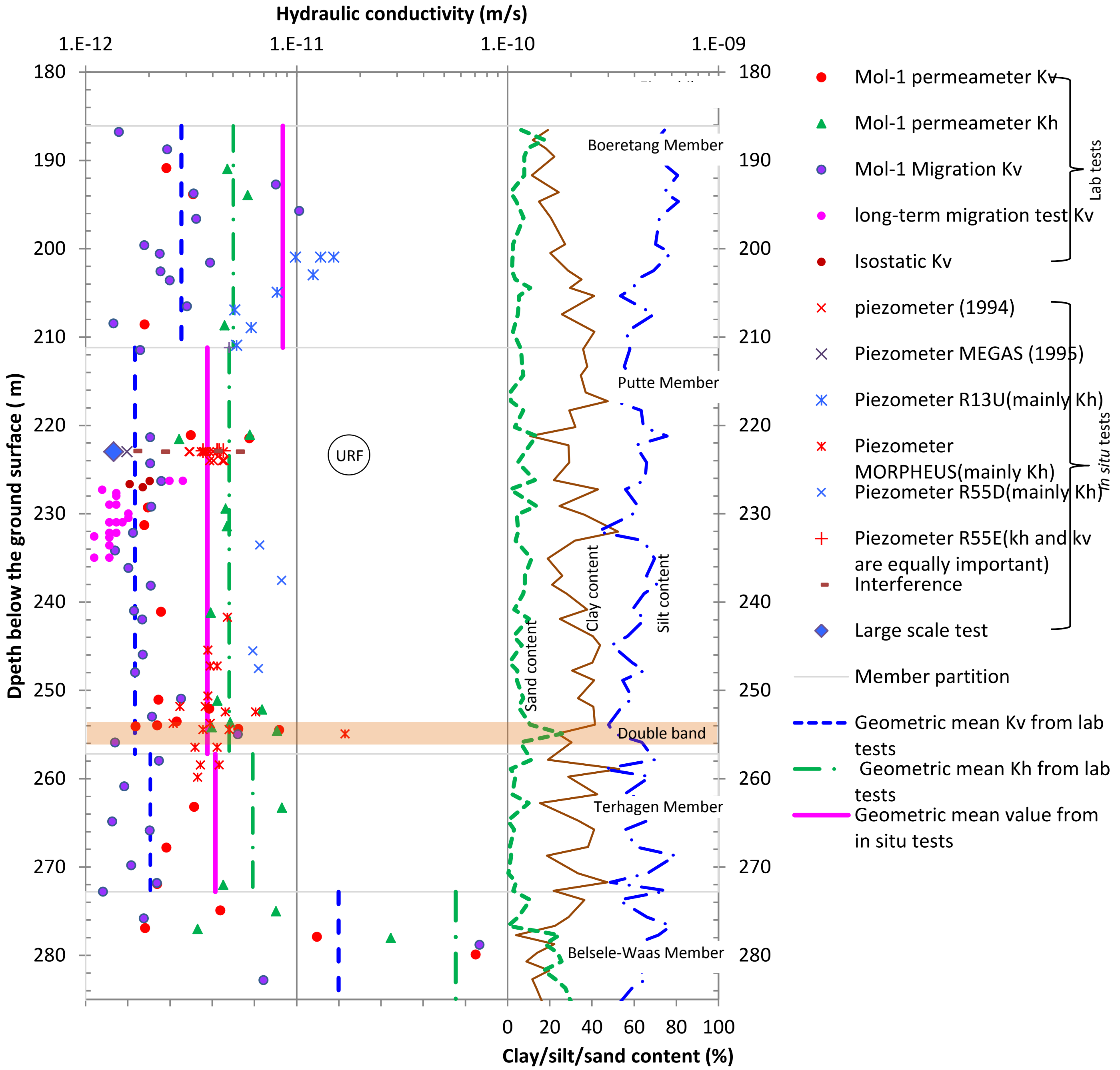

Figure 2: Hydraulic conductivity profile of Boom Clay at the Mol site based on lab tests and *in situ* tests at the HADES URF (clay: <2 µm, silt: ≥2 µm and <62.5 µm, sand: ≥62.5 µm).

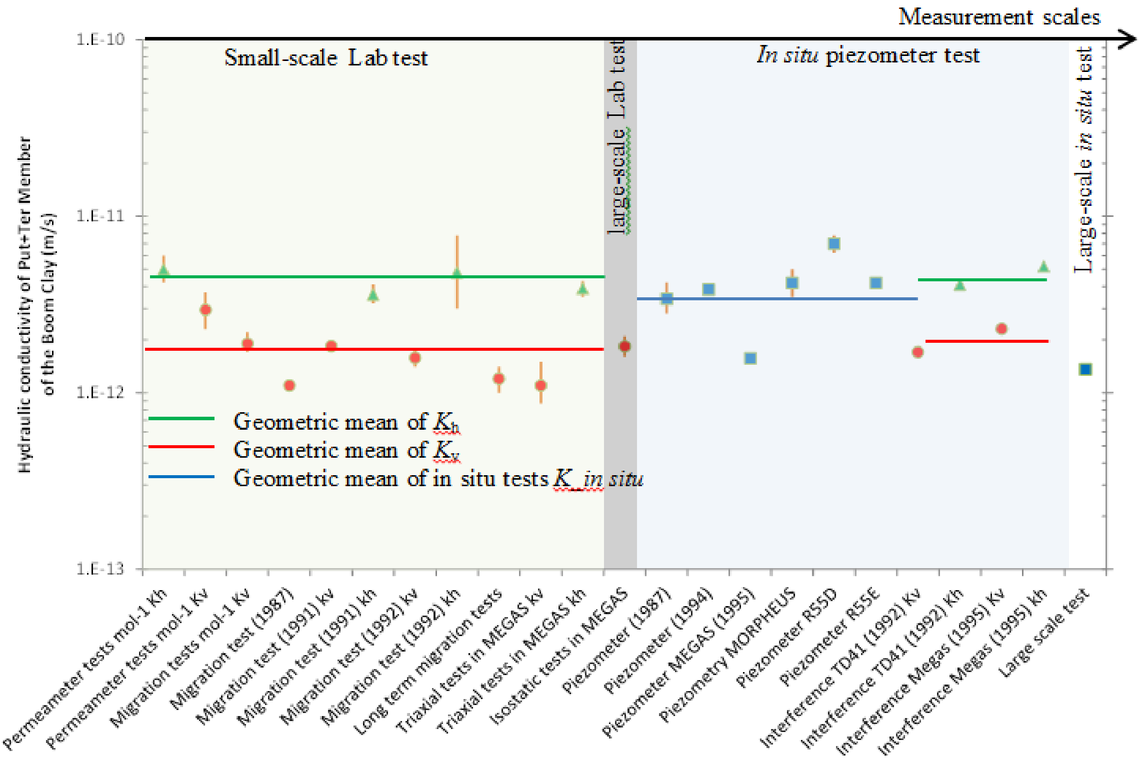

Figure 3: Overview of hydraulic conductivity values (m/s) for Putte and Terhagen Members at the Mol site. Vertical bars represent the 95% confidence interval.

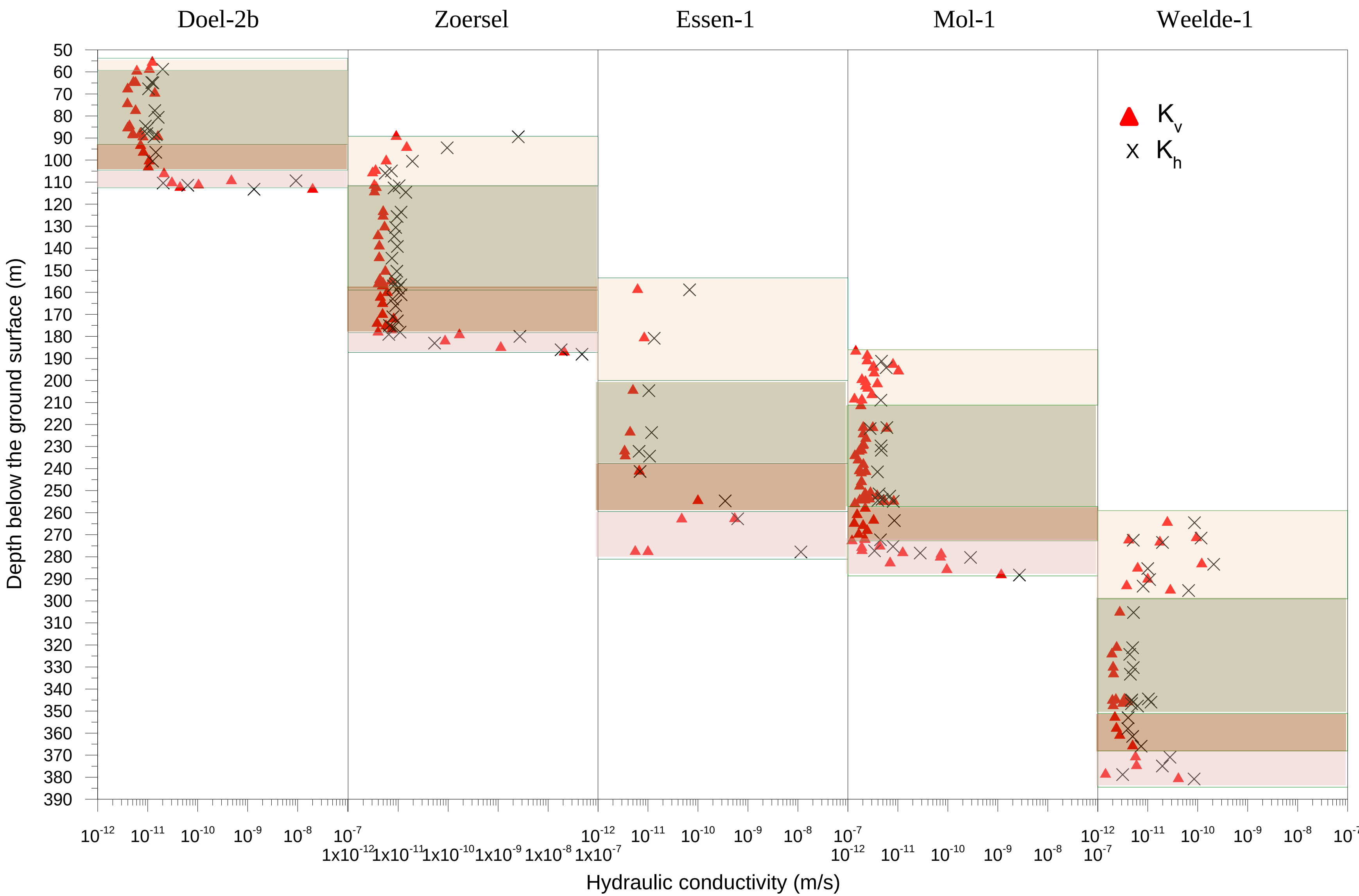

Figure 4: Spatial variability of hydraulic conductivity in five boreholes. Sub-units for all boreholes are identical (from top to bottom): Boeretang Member, Putte Member, Terhagen member, Belsele-Waas Member.

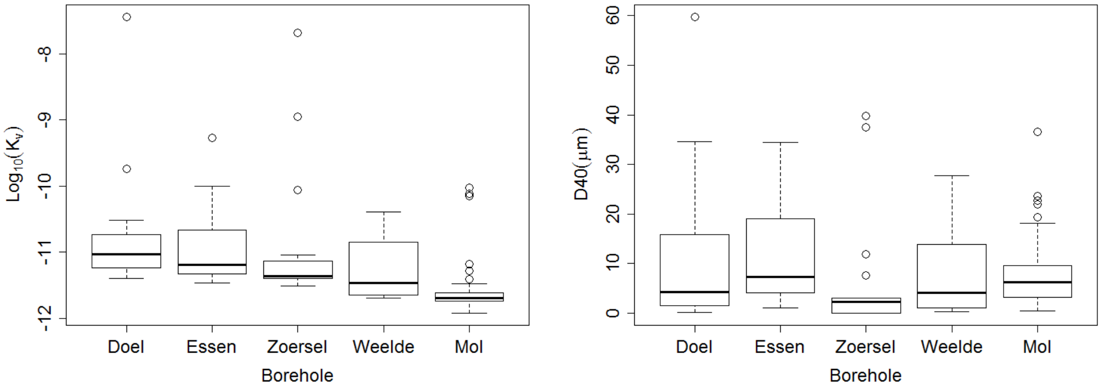

Figure 5: Box plots of vertical hydraulic conductivity (left) and *d*40 (μm , the grain-size for which 40% of the total sample has a smaller grain-size) (right) within the five boreholes.

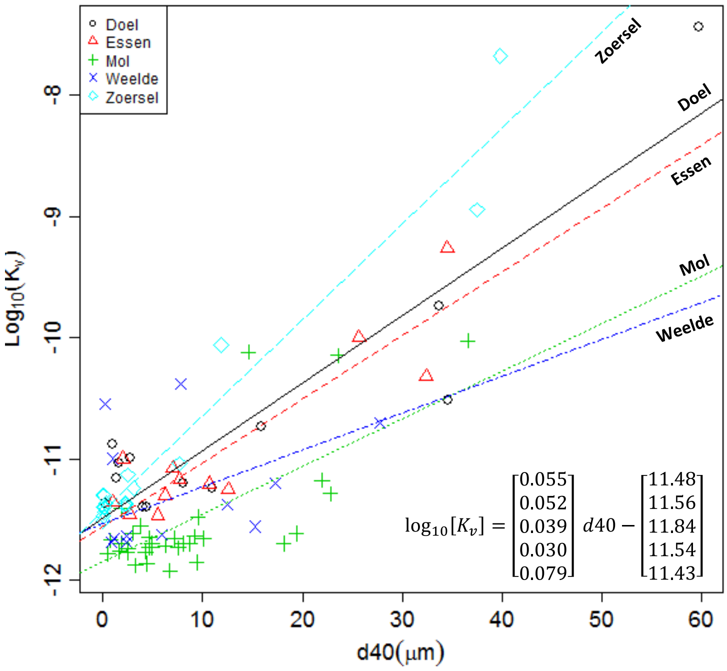

Figure 6: Scatterplot of log(K_v) and $d40$ (µm , the grain size for which 40% of the total sample has a smaller grain-size) observed on cores from the Mol-1, Zoersel, Weelde-1 and Essen-1 boreholes, and their respective linear mixed effects regression lines (random effect by borehole).

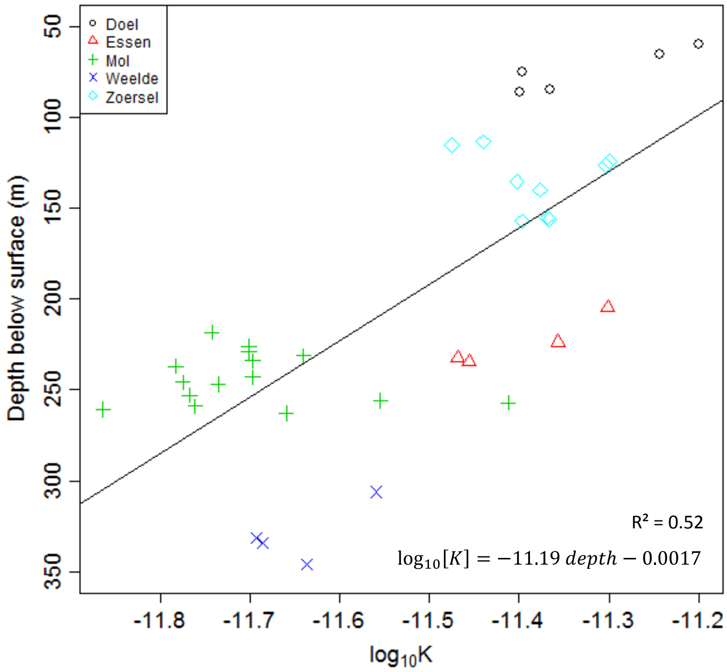

Figure 7: Trend with depth for the low K_v values (below 10^{-11} m/s) of the Putte Member.

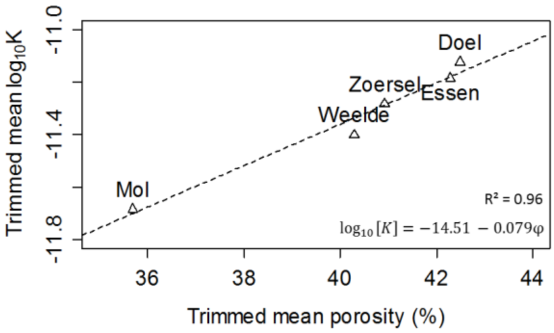

Figure 8: 50% trimmed mean porosity versus 50% trimmed mean logarithmic hydraulic conductivity for the different studied boreholes.

Table 1: The quantitative mineralogical composition ranges of the Boom Clay (from Zeelmaekers et al., 2010 & 2011).

Clay minerals	26-70 weight %
Kaolinite	2-17 weight %
Smectite	7-24 weight %
mixed-layer illite-smectite	7-23 weight %
Illite	4-18 weight %
Chlorites	1-4 weight%
Non-clay minerals	30-74 weight %
Quartz	20-61 weight %
K-feldspar	4-10 weight %
Na-plagioclase	1-4 weight %
Carbonates (mainly calcite, siderite and dolomite)	0.3-4.3 weight %
Pyrite	0.5-3 weight %
Traces of anatase and apatite	

Table 2: Stratigraphic division of the Boom Clay together with K_h and K_v for each sub unit measured by means of permeameter tests and percolation tests at the Mol-1 borehole (after Wemaere et al., 2008).

Sub unit	Stratigraphic subdivisions (m below ground surface)			Vertical hydraulic conductivity			Horizontal hydraulic conductivity		
	Top	Bottom	thickness	$n^{\S}$	K_v (m/s)‡	$s^{\dagger}$	n	K_H (m/s)	s
Boeretang	-186.1	-211.2	~25.1	16	2.8×10^{-12}	0.2	3	5.0×10^{-12}	0.1
Putte	-211.2	-257.2	~46.0	29	2.4×10^{-12}	0.2	10	4.8×10^{-12}	0.1
Terhagen	-257.2	-272.8	~15.6	9	2.0×10^{-12}	0.1	2	6.2×10^{-12}	0.2
Belsele-Waas	-272.8	-288.7	~15.9	10	1.6×10^{-11}	1.0	5	5.7×10^{-11}	1.2
Boom Clay unit	-186.1	-288.7	~102.6	64	2.8×10^{-12}		20	1.3×10^{-11}	

§ n: sample of analyses; ¶ s: the standard derivation of $\log(k) = \sqrt{(\mathrm{x} - \bar{\mathrm{x}})^2 / (n-1)}$

*K values for sub-unit are geometric means: $k_{geom} = \sqrt[n]{k_1 \cdot k_2 \ldots k_n}$. Boom Clay unit K values are harmonic mean (K_v) and arithmetic mean (K_H) of K_{geom} weighted by the thickness (H_i) of each sub unit, H is the total Boom Clay thickness:

$$K_v = H / \sum_{i-1}^{n} \left(H_i / K_{vi\,geom} \right) \text{ and } K_h = \frac{1}{H} \sum_{i-1}^{n} K_{hi\,geom} \cdot H_i$$

Table 3: Overview of the *K* values at the five regional cored boreholes (after Wemaere et al., 2008).

Unit	Doel-2b			Zoersel			Essen-1			Mol-1			Weelde-1			summary	
	n	*K*	*s*	*n*	*K*	*s*	*n*	*K*	*s*	*n*	*K*	*s*	*n*	*K*	*s*	*K*	*s*
	K_v (m/s)															K_v (m/s)	
Boeretang	2	$1.2\times10^{-11\,\mathrm{NA}}$	0.03	6	$5.5\times10^{-12\,\mathrm{a}}$	0.3	2	$7.2\times10^{-12\,\mathrm{a}}$	0.1	16	$2.8\times10^{-12\,\mathrm{b}}$	0.2	9	$1.7\times10^{-11\,\mathrm{a,b}}$	0.5	6.6×10^{-12}	0.3
Putte + Terhagen	18	$6.6\times10^{-12\,\mathrm{a}}$	0.8	24	$4.8\times10^{-12\,\mathrm{b}}$	0.1	6	$7.5\times10^{-12\,\mathrm{a,b}}$	0.5	38	$2.3\times10^{-12\,\mathrm{c}}$	0.2	15	$2.6\times10^{-12\,\mathrm{a,b,c}}$	0.2	4.3×10^{-12}	0.2
Belsele-Waas	6	$1.8\times10^{-10\,\mathrm{a}}$	1.0	4	$7.7\times10^{-10\,\mathrm{a}}$	0.9	4	$3.5\times10^{-11\,\mathrm{a}}$	0.8	10	$1.6\times10^{-11\,\mathrm{a}}$	1.0	4	$6.7\times10^{-12\,\mathrm{NA}}$	0.4	5.5×10^{-11}	0.8
Entire Boom Clay	26	$8.0\times10^{-12\,\mathrm{a}}$		34	$5.5\times10^{-12\,\mathrm{a}}$		12	$8.5\times10^{-12\,\mathrm{a}}$		64	$2.8\times10^{-12\,\mathrm{b}}$		28	$4.0\times10^{-12\,\mathrm{a,b}}$		5.3×10^{-12}	0.2
	K_h (m/s)															K_h (m/s)	
Boeretang	1	2.0×10^{-11}	-	6	3.5×10^{-11}	1.0	2	3.0×10^{-11}	0.5	3	5.0×10^{-12}	0.1	9	2.9×10^{-11}	0.6	2.0×10^{-11}	0.3
Putte + Terhagen	12	1.2×10^{-11}	0.1	23	9.0×10^{-12}	0.1	6	1.7×10^{-11}	0.7	12	5.0×10^{-12}	0.1	15	5.5×10^{-12}	0.2	8.7×10^{-12}	0.2
Belsele-Waas	4	3.6×10^{-10}	1.1	4	3.4×10^{-9}	1.1	2	2.7×10^{-9}	0.9	5	5.7×10^{-11}	1.2	4	2.0×10^{-11}	0.7	3.3×10^{-10}	1.0
Entire Boom Clay	17	5.7×10^{-11}		33	3.2×10^{-10}		10	4.7×10^{-10}		20	1.3×10^{-11}		28	1.5×10^{-11}		7.0×10^{-11}	0.7

n: number of analyses;

s: standard deviation of Log(*K*)

K_v & K_H: sub-unit values are geometric means, Boom Clay unit *K* value values are harmonic mean (K_v) and arithmetic mean (K_H) of K_{geom} weighted by the thickness (H_i) of each sub unit, *H* is total Boom Clay thickness.

[a, b] Means that are significantly different at the 5% level have different group labels. NA stands for not enough data.

Table 4: Results of analysis of variance of $\log K_v$ for the borehole location and stratigraphic member factors, for the residuals of the different models with increasing complexity. The percentages indicate the part of the total initial $\log K_v$ variance explained.

Factors	**Original data**	**Fixed effect of *d*40**	**+ Random effect by stratigraphy**	**+ Random effect by borehole**
Boreholes	**16%**	**13%**	**7%**	0%
Stratigraphy	**46%**	**3%**	0%	2%
Combined effect	**10%**	5%	**6%**	3%
Unexplained variance	28%	16%	11%	13%
Total	100%	37%	24%	18%

Table 5: Results of analysis of variance of logK_v for the borehole location and stratigraphic member factors, for the residuals of the different models with increasing complexity, and after correction for the trend in K_v with depth. The percentages indicate the part of the total initial logK_v variance explained.

Factors	**Original data**	**Fixed effect of *d*40**	**+ Random effect by stratigraphy**	**+ Random effect by borehole**
Boreholes	**<u>10%</u>**	**<u>8%</u>**	**<u>5%</u>**	0%
Stratigraphy	**<u>52%</u>**	**<u>5%</u>**	0%	**<u>3%</u>**
Combined effect	**<u>10%</u>**	5%	**<u>6%</u>**	3%
Unexplained variance	28%	16%	11%	14%
Total	100%	34%	22%	20%